The Star Formation Histories of the Bulge and Disk of M31 from Gemini North+NIRI/Altair and HST/NICMOS[1]

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ABSTRACT

We discuss H and K observations of three fields in the bulge and disk of M31 obtained with the Altair adaptive optics system and NIRI instrument on Gemini North. These are the highest resolution and deepest near-infrared observations

obtained to date of the inner regions of M31, and demonstrate the promise of ground-based adaptive optics for studying the crowded regions of nearby galaxies. We have combined our observations with previously published *HST/NICMOS* observations of nine M31 fields and have derived the coarse star formation histories of M31's bulge and inner disk. From fits to the M_K luminosity functions, we find the stellar population mix to be dominated by old, nearly solar-metallicity stars. The old populations, which we define as having age $\gtrsim 6$ Gyr, indeed dominate the star formation histories at all radii independent of the relative contributions of bulge and disk stars. Although all of our fields contain some bulge contribution, our results suggest that there is no age difference between the bulge and disk to the limit of our precision.

Subject headings: galaxies: individual(M31) — galaxies: stellar content — Local Group — instrumentation: adaptive optics — techniques: photometric

1. INTRODUCTION

The problem of galaxy formation occupies a central role in astrophysics, as it connects the study of cosmology to that of star formation and the dispersal of chemical elements. Recent observations of young galaxies at high redshift show that many massive galaxies were already in place by $z \sim 2$, challenging some models of galaxy formation (e.g. Glazebrook et al. 2004). However, the observations contain insufficient information to determine whether these galaxies are in the process of assembling disks or spheroids. Indeed, a more sensitive test of galaxy formation physics appears to be to examine the star formation histories of galaxy disks compared to those of bulges. Two recent simulations of forming disk galaxies, differing mainly in their treatment of stellar feedback, produce wildly different results (Abadi et al. 2003, Robertson et al. 2004). On one hand, the disk galaxy found in the Abadi et al. simulation has a massive old spheroid and a much younger, ~ 4 Gyr-old, disk. The simulation

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by Robertson et al., on the other hand, produces a disk galaxy dominated by ∼10 Gyr-old solar-metallicity stars, with little or no spheroidal component. Clearly, measurements of the star formation histories of spiral disks and bulges are needed to guide the physical prescriptions used in such simulations.

M31, as the nearest massive spiral to our own, offers a unique opportunity to compare a galaxy's disk and bulge stellar populations; it is distant enough to ignore its three-dimensional depth, yet nearby enough to be usefully resolved into stars. The halo and outer disk of M31 have been very extensively studied (e.g. Mould & Kristian 1986, Hodge et al. 1988, Pritchet & van den Bergh 1988, Davidge 1993, Williams 2002), with recent results providing a mix of main sequence turnoff ages (Brown et al. 2003), a mix of metallicities (Ferguson & Johnson 2001, Sarajedini & Van Duyne 2001, Durrell et al. 2004, Rich et al. 2004, Sarajedini & Jablonka 2005), and strong substructure (Ferguson et al. 2002). The crowding and differential reddening present in M31's high surface brightness bulge and inner disk, however, make them very difficult to study (Rich et al. 1993, DePoy et al. 1993, Rich & Mighell 1995, Renzini 1998, Jablonka et al. 1999, Davidge 2001, Stephens et al. 2003, hereafter S03), such that attempts to characterize their stellar populations have met with less success.

The only way to overcome the problem of crowding is to observe with higher spatial resolution, while the effects of differential reddening are best reduced by observing at longer wavelengths. Thus, large ground-based telescopes equipped with adaptive optics (AO) systems and operating in the near-infrared stand to produce the deepest observations possible of the extremely crowded inner regions of nearby galaxies, relatively free of the effects of patchy dust. In this paper, we present a derivation of the star formation history of the bulge and disk of M31 from observations taken with the Altair AO system and NIRI imager on Gemini North (Davidge et al. 2005, hereafter Paper I) and by HST/NICMOS (S03). While in Paper I and S03 we outlined the broad parameters of M31's bulge and inner disk stellar populations, in this paper we perform an automated fit of a set of model isochrones to the data to objectively measure the star formation histories as a function of radius in M31. We describe our observations and data reduction in §2 and the intricacies of the NIRI/Altair photometry in §3. §4 discusses our completeness and photometric errors, while in §5 we describe the derivation of the star formation histories and report our results. Our conclusions are summarized in §6.

2.   OBSERVATIONS AND DATA REDUCTION

As described above, we used data from two sources for the analyses in this paper. First, we obtained data of three fields located within $9'$ of the center of M31 and one more distant field with the Altair AO system and NIRI infrared camera on Gemini North on the nights of 18-19 November 2003, as part of Gemini's System Verification program. These data, the details of which we presented in Paper I, yielded JHK images with resolutions of $0\rlap{.}''16$ (J), $0\rlap{.}''10$ (H) and $0\rlap{.}''09$ (K) at radii within $9''$ of the central guide stars, becoming worse towards the edges of the $22\rlap{.}''5 \times 22\rlap{.}''5$ field. The images are not quite diffraction-limited, as they were taken before the source of an internal vibration in Altair was discovered; NIRI/Altair is now capable of producing images with slightly higher resolution than we achieved with our data. For the purposes of this paper, we used only the H and K images, which are considerably deeper than the J images, and did not consider the distant Disk 1 field, which does not have enough sources in it to warrant more analysis than that already presented in Paper I. The second source of data used here are the J and K photometry derived by S03 from *HST/NICMOS* observations of 9 fields in M31. Figure 1 shows the locations of the NIRI/Altair and NICMOS fields with respect to M31. Example images of the NIRI/Altair fields can be seen in Figs. 1 and 2 of Paper 1.

We reduced the NIRI/Altair data independently of Paper I, but following the basic steps outlined therein. In brief, we followed the standard NIRI imaging reduction example found in the Gemini IRAF package to remove the dark current, create and subtract a sky image, create and divide by a flat field, correct for bad pixels, and align and combine the individual exposures into single images. The step that required the greatest care was the stacking of the individual dithered exposures, as NIRI/Altair images contain some optical distortion. We corrected for this by allowing the rotation and linear scale of individual images to vary slightly during stacking; the corrections typically amounted to $\sim$1 pixel over the entire field of view. Once aligned, the images were averaged together with no scaling applied; as all of the M31 images were taken at airmasses between 1.1 and 1.2, the difference in atmospheric extinction between images should be $<1\%$.

3.   PHOTOMETRY OF NIRI/ALTAIR IMAGES

We made photometric measurements on the combined NIRI/Altair M31 images using DAOPHOT (Stetson 1987) and ALLSTAR (Stetson & Harris 1988). We identified stars using only one pass through the FIND procedure. We constructed PSFs using $\sim$200 bright stars in each image, using an iterative procedure so as to remove contaminating fainter companions. The PSF was allowed to vary quadratically with position. We defined the PSFs out to

radii of 0$\rlap{.}''$22 (10 pixels), or $\sim 3\times$ the FWHM. Because of the incomplete correction for atmospheric turbulence provided by AO, a significant fraction of the light in the PSF is distributed over the scale of the seeing disk, which has a FWHM of $\sim$30-40 pixels (0$\rlap{.}''$66 - 0$\rlap{.}''$88) in our images; the Strehl ratio, in other words, is <1. Moreover, anisoplanaticity causes the fraction of light scattered into this larger halo to increase with increasing distance from the guide star. Because our M31 images are extremely crowded, we cannot correct for the entire contributions of the halos using the images themselves. Instead, we applied a partial correction to our PSF photometry by measuring aperture photometry of the bright PSF stars out to a 15-pixel (0$\rlap{.}''$33) radius after neighboring stars had been PSF-subtracted. Figure 2 shows an example of the differences between the PSF magnitudes and the aperture magnitudes, which are a clear function of radius. We fit least-squares linear relationships to the PSF minus aperture magnitude differences for each of the images and applied them to the PSF photometry. In order to keep the corrections small, we excluded photometry for any stars outside 400 pixels (8$\rlap{.}''$8) in radius from the central guide stars; we also excluded photometry of stars closer than 20 pixels (0$\rlap{.}''$44) to the guide stars, as these are contaminated by the guide star halos.

Next, we calibrated the photometry by two independent methods. The first method was to use aperture photometry of the photometric standard stars FS103 (Hawarden et al. 2001) and AS40-1 (Hunt et al. 1998), which were observed on the same nights as the M31 fields and at similar airmasses, for a total of 12 independent observations in each filter. From the uncrowded standard star images, we found that an aperture of 100 pixels (2$\rlap{.}''$2) in radius was needed to enclose >99% of the light from the stars (as judged from the asymptotic value of the growth curve), with standard deviations of 0.02 (H) and 0.03 (K) magnitudes in the zero point using this aperture. Using the smaller 15-pixel radius aperture, we found that we needed to apply corrections of 0.40$\pm$0.09 (H) and 0.32$\pm$0.06 (K) magnitudes to account for the light outside the aperture. The larger standard deviations of the photometry with the smaller apertures are the result of temporal Strehl ratio variations among the set of standard star images, and reflect the true uncertainty of our photometric zero points introduced by changing atmospheric conditions during our observations.

The second calibration method was to fit our PSFs to the wings of the saturated central guide stars, which have accurate photometry from 2MASS (Skrutskie et al. 1997), and are several magnitudes brighter than the M31 background, making crowding a non-issue. The advantage of this approach is that it avoids the uncertainty of tying the calibration to observations taken at a different time and under different conditions. The disadvantages are that it relies on a large extrapolation of the contribution of the saturated portion of the guide stars (albeit an extrapolation based on information from 200 stars in each image), and that the guide stars, while bright, are not well-established standards. Despite these drawbacks,

we felt that this second approach provides a useful check on the reliability of our calibration. As shown in Table 1, the two calibration methods agree well to within the uncertainties, the exception being the K zero point of the Disk 2 field, where they differ by 0.25 magnitudes. As the guide star in this field is the brightest, with 55% of its light in the saturated core, we attribute the difference either to an error in the PSF extrapolation or, as suggested in Paper I, to intrinsic variability of the guide star itself. We thus rely on the standard star calibration for the remainder of this paper, and note that the independent check of using the guide stars to calibrate the photometry gives us confidence that our zero points are accurate to at least 0.1 magnitude, if not better.

Once the photometry was calibrated, we produced color-magnitude diagrams (CMDs) by finding matches within ∼2 pixels of each other from the lists of H and K photometry. Figure 3 shows the CMDs. The zero points of these CMDs agree to within ∼0.1 magnitudes with those published in Paper I; the main difference between them is the use of an aperture correction that varies as a function of position in the current paper. We can check whether the photometry published here represents an improvement over Paper I by plotting $H - K$ vs. radius, as is done in Figure 4; because the red giant branch (RGB) and asymptotic giant branch (AGB) sequences are nearly vertical in the $H - K, K$ plane, and we do not expect population gradients across the small NIRI/Altair field of view (∼85 pc at the distance of M31), residual Strehl variations will likely appear as gradients in $H - K$. Figure 4 shows that small $H - K$ gradients exist in the photometry published in Paper I, but have been successfully removed in the photometry presented here.

4. COMPLETENESS AND ERROR ANALYSIS OF NIRI/ALTAIR PHOTOMETRY

We calculated the completeness of our photometry and the photometric errors through two sets of artificial star simulations. The first employed the "traditional" technique of adding a sample of artificial stars to multiple copies of the original H and K images and rerunning the steps of our photometric pipeline on each of these images. We selected the input stars by choosing 20000 stars over the luminosity range $-7.3 \leq M_K \leq 1.0$ from a 10-Gyr solar metallicity Girardi et al. (2002; hereafter G02) isochrone, which we distributed 50 at a time to 400 copies of the original H and K images. We did not consider inserting stars with a range of color, as the photometric errors and completeness are almost entirely functions of magnitude. We converted the absolute H and K magnitudes to apparent magnitudes assuming an M31 distance modulus of 24.45 (e.g. Freedman & Madore 1990, Stanek & Garnavich 1998, Mochejska et al. 2000), applied our photometric calibration in

reverse to bring the stars onto the raw magnitude system, and assigned random positions to the stars. After using ADDSTAR to place the artificial stars in the images and running our DAOPHOT/ALLSTAR pipeline on the artificial images, the output lists of photometry were culled to exclude matches with stars with positions within 0.5 pixels and with magnitudes within 0.1 of the original photometry. Artificial stars were considered recovered if their entry in the input list contained a match in the culled output list within 2.5 pixels ($0\rlap{.}''055$) and contained a counterpart in the other filter within $\sim$2 pixels, the same matching radius used to create the observed CMDs. These radii were set through an examination of of the distributions of the position differences of matches.

The second set of simulations consisted of photometry of images containing entirely artificial stellar populations, as done e.g. by S03, and designed to match our real images in field of view and surface brightness. For these simulations, we selected stars from a 12-Gyr solar metallicity G02 isochrone with a Salpeter (1955) IMF, and included stars as faint as $M_K = 4$. These faint stars lie roughly 7.5 magnitudes below our detection limit, but were included to accurately model the fluctuations in background. We produced simulated H and K images for each of the Bulge 1, Bulge 2, and Disk 2 fields. We selected a sufficient number of stars to match the total luminosities derived from Kent's (1989) r-band surface brightness model, assuming $r - K = 2.9$, $(m - M)_0 = 24.45$, and $A_K = 0.024$; for the Bulge 1 field, 6.6×10^6 stars were simulated, while the Bulge 2 and Disk 2 fields contain 2.8×10^6 and 1.1×10^6 stars, respectively. Our choice of an old isochrone ensures that our simulations represent the most severe possible crowding; had we used a younger isochrone, the number of stars needed to match the observed surface brightnesses would be smaller, and the crowding less severe. We assigned uniformly distributed random positions to the stars, which is appropriate because the NIRI/Altair field of view is small compared to M31's surface brightness gradient. We did not use ADDSTAR to insert the stars into images, as this would have been too time-consuming. Instead, we produced 16 different versions of each of the artificial images, each one convolved with the DAOPHOT PSF calculated at the different positions of a 4×4 grid with grid spacing of $4\rlap{.}''4$ (200 pixels). We then combined the 16 different versions together using a weighted average that resulted in an image with the PSF bilinearly interpolated over the 4×4 grid, thus approximating the PSF variability in our real images. After adding Poisson noise from the stars and sky, photometry of these images was produced using the same DAOPHOT/ALLSTAR pipeline used for the real M31 images and the same photometric calibration; the CMDs were produced by the same process described in §3. For the purposes of computing completeness and photometric errors from the simulation, we paired each star measured by ALLSTAR with the brightest star in the input list found within 2.5 pixels ($0\rlap{.}''055$). We picked the brightest star rather than simply the closest star, as within the area of a resolution element, the brightest star contributes the

majority of the flux to the output image.

Figure 5 shows the similarity of the depth of the artificial CMDs to the real CMDs, to be compared to Figure 3. The scatter at faint magnitudes is also reproduced by the simulation; for example, at $K \sim 19.5$, σ_{H-K} is 0.14 in the observed Bulge 1 CMD and 0.12 in the simulated one. At bright magnitudes, the observed widths of the RGB and AGB branches are much wider than expected by purely photometric errors; for example, at $K \sim 17.5$, σ_{H-K} is 0.074 in the observed Bulge 1 CMD and 0.024 in the simulated one. This could indicate metallicity dispersion and/or differential reddening, as noted in Paper I. Figure 6 shows the average photometric errors and completeness derived from the traditional artificial star tests; those derived from the entirely simulated images are very similar, and so are not plotted. We also show the photometric errors predicted by the Olsen et al. (2003) analytical model of crowding. The good agreement between the analytical model and the simulations at the bright end demonstrates that crowding dominates the photometric errors at bright magnitudes. The model correctly predicts that the errors in $H - K$ color are *smaller* than those in K magnitude, as only happens in the case of crowding, where photometric errors in different filters are correlated. As concluded in Paper I, the crowding is not severe enough to explain the large number of bright red stars in the M31 CMDs as being photometric blends. Very few such stars are seen in the simulated CMDs in Figure 5, as is expected because the crowding-induced errors are $\lesssim 10\%$ down to $K \sim 20$. At fainter magnitudes, the predictions of the analytical crowding model fall below the errors in the simulation, indicating the increasing contribution of Poisson noise to the errors.

4.1.   Comparison of NIRI/Altair and NICMOS Photometry

In Figure 7, we show the combined $(H-K)_0, M_K$ CMD of the 9 NICMOS fields from S03 compared to that of the three NIRI/Altair fields presented here. In constructing the CMDs, we have employed a distance modulus $(m - M)_0 = 24.45$, dust extinction $A_K = 0.1$, and $E(H - K)/A_K = 0.571$. The excellent match between the NICMOS and NIRI/Altair CMDs gives us confidence that our H and K photometry is well-calibrated. Plotting a histogram of color for all magnitudes $-6.25 \leq M_K \leq -5.75$, we find that the two distributions have averages of $< (H-K)_{0,\mathrm{NICMOS}} >= 0.322$ and $< (H-K)_{0,\mathrm{NIRI/Altair}} >= 0.285$, with standard deviations of 0.064 and 0.081 magnitudes, respectively (discounting points further than 3σ from the means).

We are concerned, however, about the J photometry published in S03. Figure 8 compares the combined M31 NICMOS $(H-K)_0, M_K$ CMD with the $(H-K)_0, M_K$ CMD of the LMC Bar from the 2MASS Point Source Catalog (Cutri et al. 2003), where we have used

$(m - M)_0 = 18.5$ and $A_K = 0.025$ (Zaritsky et al. 2004) for the LMC Bar. The histograms of color for stars with $-6.25 \leq M_K \leq -5.75$ clearly indicate that the LMC sequence lies $\sim$0.1 magnitude blueward of the M31 sequence. If we ascribe the difference in color to lower metallicity and/or younger age in the LMC, then we expect the $(J - K)_0, M_K$ LMC CMD to be $\sim$0.2 magnitudes bluer than that of M31. However, as seen in Figure 9, the RGB and AGB stars in the LMC are actually ~ 0.05 magnitudes *redder* in $(J - K)_0$ than in M31. We thus suspect that the J photometry of S03 is too bright by as much as 0.25 magnitudes, and thus do not consider it in this paper. This suspicion is deepened by the fact that the G02 isochrones correctly predict the $(J - K)_0$ fiducial colors of globular cluster sequences from Ferraro et al. (2000) to within 0.03 magnitudes, ruling out error in the isochrone colors.

5. STAR FORMATION HISTORIES

Over the past few years, extracting star formation histories from observations of mixed stellar populations, a task that Schwarzschild (1965) described as "somewhat hopeless", has become routine (see Dolphin 2002 for an overview). There are many reasons for this change in outlook. Perhaps most important is the availability of digital detectors yielding excellent semi-automated photometric measurements; also important are the increased resolution of modern telescopes, better understanding of stellar structure and evolution, and the recent development, coupled with greater computing power, of automated techniques that measure the star formation histories by statistical comparisons of models and observations (e.g. Tolstoy & Saha 1996, Aparicio et al. 1996, Dolphin 1997, Hernandez et al. 1999, Harris & Zaritsky 2001). While these techniques differ in detail, all rely on the ability to generate synthetic observations from model isochrones, given a set of parameters (e.g. age, metallicity, distance, reddening, binary properties, and IMF slope) describing the model stellar population. An important step in the production of the synthetic observations is the modeling of the photometric errors and completeness; as seen above, these are influenced by a combination of crowding and instrumental noise, and are best estimated through artificial star tests. Finally, all of the techniques derive the star formation history by computing the likelihood that the observations are a representation of a given model. Where the techniques differ most is in their approach to searching the likelihood space for the best solution.

In this paper, we derive the first detailed star formation histories of the bulge and inner disk of M31. To this end, we used the software developed by us in Olsen (1999) and Blum et al. (2003) (which is based on the technique outlined by Dolphin 1997 and Dolphin 2002) to fit model stellar populations to the K luminosity functions (LFs) of our fields. We assumed that our LFs may be modeled by linear combinations of G02 isochrones specified by discrete

ages from the set {1, 3, 5, 10} Gyr and discrete metallicities from the set Z={0.0001, 0.0004, 0.001, 0.008, 0.019, 0.03}. Our choice of basis isochrones and our choice to model the K LFs instead of the complete CMDs were driven by experiments, which will be described fully in a forthcoming paper, in which we used our software to derive the star formation history of the Large Magellanic Cloud (LMC) from 2MASS (Cutri et al. 2003) photometry of its evolved stars. In brief, we found that by using only the K_s LF and the G02 isochrones, our results were qualitatively consistent with star formation histories derived from deep optical *HST* photometry; fits to the full 2MASS CMD of the LMC did not provide as good agreement. This is in part because the colors in the models adopted here employ solar-scaled opacities, which are inappropriate for chemically processed AGB stars (Marigo et al. 2003). These results are in general agreement with Cioni et al. (2005), who performed similar analysis of the 2MASS LMC photometry; Marigo et al. (2003) show the effort needed to qualitatively reproduce the features in the full 2MASS LMC CMDs.

We employed a distance modulus of $(m - M)_0 = 24.45$ and a Salpeter (1955) IMF throughout our analysis. We set $A_K = 0.1$ on the basis of work by Xu & Helou (1996) and Haas et al. (1998), who measured the optical depth due to dust in M31 through modelling of the emission detected by IRAS and ISO. Haas et al. (1998) found an average $\tau_V \approx 0.5$ over most of the M31 disk, with higher τ_V in the 10 kpc ring and in a knot $5'$ from the nucleus; none of our fields, however, lie within this knot, and only F2 and F280 (S03) lie near the 10 kpc ring. Xu & Helou (1996) found average $0.7 \lesssim \tau_V \lesssim 1.7$ over the range of radii of our fields, with $\tau_V \sim 0.8$ being appropriate for most of our fields. Taking $A_V = 1.086\tau_V$ and adopting $A_K/A_V = 0.11$ (Schlegel et al. 1998), we find $A_K \approx 0.1$. We note, however, that this represents only an average, whereas the true extinction could explore values between $0.05 \lesssim A_K \lesssim 0.2$. The Milky Way foreground extinction of $A_V = 0.062$ (Schlegel et al. 1998) makes a negligible contribution to the total absorption, and so is neglected here. For these data, we did not bother including different IMF slopes or binary star fractions in our models. Because the mass range spanned by the upper RGB and AGB is very small, changing the IMF would affect only the total mass represented by the star formation history. In addition, the contributions of binary companions to the luminosity of bright RGB and AGB primaries, which are in a short-lived phase of stellar evolution, are negligible.

Given the above assumptions, our goal was to find the combination of age and metallicity with maximum likelihood of representing our observations. To do this, we first computed the theoretical K LFs corresponding to each combination of model parameters. The first step in this computation was to produce separate K LFs for each of the 24 combinations of age and metallicity from the G02 isochrones; in doing this, we assumed a width of 1 Myr for each isochrone (yielding a practically instantaneous burst) and a star formation rate of 1 $M_\odot$ yr^{-1}. Using a wider width in age for the isochrones would not affect our results, as the K

LF has only coarse sensitivity to age and metallicity. We used a bin size of 0.16 in K, which is small enough to resolve the differences between the input isochrones. Next, we translated each of the LFs to the distance of M31 and added the effect of extinction by dust. We then convolved each of the LFs with an adaptive Gaussian kernel representing the photometric errors derived from our artificial star tests, and multiplied them by a curve representing the completeness of our observations as a function of observed K. Finally, we trimmed the model LFs to include only the portions with completeness greater than 50%; doing this ensures that our results are not adversely affected by incompleteness and photometric bias. These 50% limits are listed in Table 2; with the exception of F1, these limits include RGB tip stars of all ages and metallicities considered here.

Figure 10 illustrates the population-sensitive features of the K LF. At higher metallicity, the RGB tip becomes considerably brighter in K, while the AGB tip brightens also. The RGB tip becomes brighter with increasing age for ages below ~ 5 Gyr, while the AGB tip becomes fainter with increasing age at all ages. Because none of these trends are linear, there is hope of extracting both age and metallicity from the detailed shape of the K LF.

After binning and trimming our observed K photometry in the same way as was done for the model LFs, we used the minimization routine `amoeba` (Press et al. 1992) to find the model with maximum likelihood of representing our observations. We computed the likelihood assuming Poisson-distributed data, as discussed by Dolphin (2002); in practice, this meant minimizing the parameter $\chi^2_\lambda = 2\Sigma_i m_i - n_i + n_i ln(n_i/m_i)$ (Mighell 1999, Dolphin 2002), where m_i is the number of stars predicted by the model in the ith bin and n_i is the number of observed stars in the bin. We allowed the routine to form a linear combination from any of the 24 models representing different ages and metallicities. The coefficients of this linear combination are the best-fit star formation and chemical enrichment history, given our assumptions about A_K, the distance modulus, and the IMF. We also computed fits adopting $A_K = 0.0$ and $A_K = 0.2$, so as to explore the effect of possible errors in our assumptions about the dust extinction and/or zero point errors in our K photometry. In order to verify that having both age and metallicity as free parameters is warranted, we also computed fits to the LFs in which only one of the two variables (age, metallicity) was allowed to vary, the other one being held at a constant value.

For the solutions with $A_K = 0.1$ and having full freedom in age and metallicity, we derived errors in the fitted star formation rates by running our fitting procedure on bootstrapped samples of our original data. These samples were created by randomly drawing N stars from our original CMDs, where N is the number of stars in the original CMD, but permitting repeat draws of the same stars. From the best-fit star formation rates for these bootstrapped samples, we calculated the 1-σ standard deviations of the star formation

rates in each bin; we call these our measurement errors. A separate question is whether our best-fit models are statistically likely representations of our observations. To address this question, we computed the expectation value and variance of the χ_λ^2 parameter from our best-fit models, and then calculated the probability P_λ that values of χ_λ^2 as high as the ones we measured could arise by chance. As discussed by Dolphin (2002), in the limit of large n_i and m_i (in which a Poisson distribution is indistinguishable from a Gaussian), χ_λ^2 has an expectation value of 1 and a variance of 2 in each bin i; for smaller m_i, the expectation value and variance deviate slightly from these values.

Table 3 summarizes our fits of the population mixes in the Bulge 1, Bulge 2, and Disk 2 fields observed with NIRI/Altair and the NICMOS fields from S03. The pieces of information included in the table are an identifier for each solution, the A_K used in the solutions, the best-fit star formation rates in each of the age and metallicity components with errors in parentheses where calculated, the χ_λ^2 for each fit, a number $\sigma_{\chi_\lambda^2}$ representing the extent to which the fitted χ_{lambda}^2 deviate from the expectation values for the models (calculated as $(\chi_\lambda^2 - <\chi_\lambda^2>)/<\sigma>$, where the bracketed quantities are the expected mean and variance of χ_λ^2 for each model), and the probability P_λ (in %) that χ_λ^2 as high as the ones listed could have arisen by chance. If the LFs were truly drawn from the given models, then we expect $P_\lambda \sim 50\%$; low values of P_λ are indicative that the models are not good fits. The identifiers consist of a combination of the field name and a number between 1 and 13. The number 1 is reserved for the solutions with $A_K = 0.1$ and full freedom in fitting the ages and metallicities; numbers 2 and 3 solutions with $A_K = 0.0$ and 0.2, respectively; numbers 4-7 solutions with $A_K = 0.1$ and ages held to fixed values; and numbers 8-13 solutions with $A_K = 0.1$ and metallicities held to fixed values.

Our preferred solutions are those with $A_K = 0.1$, as we believe this to be closest to the correct value of the dust extinction. However, in many cases one or the other of the $A_K = 0.0$ and $A_K = 0.2$ solutions provide better statistical fits. We examine the effect of adopting these other fits in §5.2 There are also four fields, F2, F3, and F4, F280, where one or more of the fixed-age/fixed-metallicity solutions provide nearly as good fits. However, at least in the cases of F3 and F4, these other solutions are not qualititatively different from the solutions with full freedom in fitting the ages and metallicities. Thus, on the whole, there is good evidence that, given our assumption about A_K and the distance modulus of M31, a mix of ages and metallicities are required to model its stellar populations. In the case of F280, however, the statistical likelihood P_λ of many of the fits are so high that we can only conclude that F280 is not well fit by exclusively 1 Gyr, 5 Gyr, or 10 Gyr-old populations.

Finally, in seven of the fields (Bulge 1, Bulge 2, F1, F4, F170, F174, and F177) the statistical likelihood P_λ of the fits is <1%, with F4 and F174 being the worst. In these

cases, we found that we could typically obtain an order of magnitude higher likelihood if we excluded the faintest 1-2 bins of the LFs, or, in the case of F4, the bins containing the brightest two stars. Running new fits with these bins excluded did not appreciably change the best-fit star formation histories, so for overall consistency, we report only the fits to the full LFs. We suspect, however, that the reason for the low P_λ of some of our fits is error in our completeness and photometric error measurements at faint magnitudes.

5.1. Age and Metallicity Resolution

To demonstrate the age and metallicity resolution of our data, we performed three sets of tests using simulated observations drawn from the set of G02 isochrones. Our first test consisted of a model population with uniform extinction A_K=0.024, four bursts of star formation at 10, 5, 3, and 1 Gyr, and increasing metallicity with age, and is depicted as a "population box" (Hodge 1989) in Figure 11. Stars were drawn randomly from this population in numbers to match the surface brightness of our Bulge 2 field; these stars were then paired with stars from our artificial star tests, the results of which we used to apply photometric errors and to decide which of the simulated stars would be lost through incompleteness. The result was an LF with properties similar to that of our Bulge 2 field, but with a known input population mix. Figure 11 shows the recovered population box obtained by running the artificial LF through our software, and compares the recovered age and metallicity distributions with the input ones. We see that our solution closely recovers the overall age and metallicity distributions of the input population. In addition, with the exception of the oldest age bin, the dispersion in metallicity at a given age is of order our bin size.

Our second test isolated the oldest populations, which are the most difficult to discriminate. Our input population, as shown in Figure 12, consisted of bursts at 5 and 10 Gyr and solar metallicity. The fit recovered approximately the correct age and metallicity distributions, with a dispersion of order the bin size in the fitted metallicities, and demonstrates that we can faithfully discriminate between intermediate-age (5 Gyr) and old (10 Gyr) populations.

Up to this point, the tests we have described employed exactly the same isochrone set to produce the input populations as were used to derive the solutions, whereas nature is unlikely to be so cooperative. To test the effect of this idealization, we conducted a third test where the input population approximated a constant star formation rate from 1 to 10 Gyr with linearly increasing metallicity. We used the G02 isochrones, interpolated onto a grid with 0.1-Gyr spacing, to produce the input population, while for our solution, we continued to

use only the isochrones from the discrete sets age={1, 3, 5, 10} Gyr and Z={0.0001, 0.0004, 0.001, 0.008, 0.019, 0.03}. In Figure 13, we show both the input population box and that recovered by the best-fit solution to the simulated K LF. With the exception of the addition of a range of metallicities in the 10 Gyr age bin, our solution recovered the approximate metallicity distribution; it also recovered roughly the correct star formation rates in the 1-5 Gyr range. However, the star formation in the 10 Gyr bin far exceeds the input value; indeed, it appears that all of the star formation with ages 6 Gyr and above was drawn into the 10 Gyr bin. This test thus shows that while we can pick out ∼5 Gyr populations with our basis set of models, populations older than ∼6 Gyr will all appear to have the same age.

5.2.   Results and Discussion

As an illustration of the results, Figure 14 shows the population boxes (Hodge 1989) of the best fits to the NIRI/Altair observations and to one of the NICMOS fields. We also show the model LFs compared to the observations as well as a comparison of the model and observed CMDs, expressed as Hess diagrams, where we have assumed $E(H-K) = 0.571A_K$ (Schlegel et al. 1998). As seen in the figure, while the models provide good fits to the LFs, the models we used are not designed to fit the full near-infrared CMDs; the data consistently fall to the red of the models by ∼0.04 magnitudes in the mean color. This color difference is small enough to be unimportant for our conclusions if the error were all in K, but would introduce population differences if we fit the full CMDs rather than the M_K LFs. We suspect, however, that the problem lies mainly in the model H magnitudes, because the Ferraro et al. (2000) $(J-K)_0$ fiducial colors of Galactic globular clusters agree nicely with the Padova isochrones, while the $(J-H)_0$ fiducial colors from Valenti et al. (2004) are systematically bluer by ∼0.04 magnitudes than the isochrones. See Marigo et al. (2003) for a deeper investigation of the physics needed to fit near-IR photometry of evolved stars.

We examine the age and metallicity trends more broadly in Figure 15, where we plot the mean ages and metallicities (where we define [M/H]≡ $\log Z/Z_\odot$) of our fits with $A_K = 0.1$ versus radius on the sky/bulge-to-disk ratio as well as the relative contributions of each of the stellar population components. Because our fields contain contributions from both bulge and disk components, we use radius on the sky rather than deprojected radius in the M31 disk plane for these plots. We find that the average age of the fits is ∼ 8 Gyr with an r.m.s. of ∼1.5 Gyr at all radii. Examining the contribution of the individual age components of our fits, the ∼10-Gyr population dominates the fits at all radii and bulge-to-disk ratios, contributing ≳60% of the star formation over M31's lifetime in all fields. Where the 10-Gyr contribution is lowest, the 5 Gyr population contributes correspondingly more to the

overall star formation, while the 1 and 3 Gyr populations never contribute more than $\sim$20% of the total star formation. Examining the mean metallicities, we find that at a radius of $5'$ from the center, the mean metallicities are near solar with an r.m.s. of $\sim$0.5 dex. The fits suggest that the mean metallicity drops by $\sim$0.5 dex in fields with B/D $\sim$0.3 – 1, with an additional hint that the metallicity is also slightly lower at the smallest radii. In the inner bulge, however, this drop in mean metallicity is due entirely to the sudden contribution of a substantial [M/H]=-2.3 population, which we believe to be spurious, as discussed further below. Examining the individual metallicity components shows that while all contribute to some degree, the fits are indeed dominated by the components with [M/H]≥ -0.5 at nearly all radii. Our results are independent of whether the photometry derives from NIRI/Altair or HST/NICMOS.

We demonstrate the effect of adopting either the fits with $A_K = 0.0$ or $A_K = 0.2$ in Figure 16. The mean metallicities are $\sim$0.25 dex lower in the $A_K = 0.2$ fits and $\sim$0.25 dex higher in the $A_K = 0.0$ fits than in the case of $A_K = 0.1$. The mean ages are $\sim$1 Gyr younger in the case of $A_K = 0.2$ compared to $A_K = 0.1$, while the $A_K = 0.0$ mean ages are similar, with the exception of F280, the field most distant from the M31 center. However, as stated previously, this field has a very uncertain star formation history on account of its low number of stars. In Figure 17 we show the result of picking those fits with highest P_λ and A_K in the range 0.0 – 0.2. The mean ages and metallicities shown are nearly identical to those of Figure 15. We thus conclude that aside from F280, our results are insensitive to changes in A_K at the level of $\pm$0.1 magnitudes. The conclusion that older ($\sim$6+ Gyr) populations with [M/H]$\sim$-0.5 – 0.0 dominate M31 for fields with B/D$\geq$0.3 appears robust.

How well does our method break the age-metallicity degeneracy often found in stellar populations studies? The tests described in §5.1 do not reveal any such degeneracy in the models at our age and metallicity resolution. We caution, however, that our breaking of the age-metallicity degeneracy in some cases depends on the existence or not of a few ($\sim$10) bright AGB stars; indeed, these are the stars from which much of our age sensitivity derives. Also, because the models are not perfect descriptions of our observations, there exists the possibility that some of our models are nearly degenerate with respect to the data or that models that are not representative of the true populations could drive the fits. In these cases, we would expect to see correlations between pairs of model parameters fit to different fields. The right-hand panels of Figure 15 show that there does appear to be correlation between some of the components in our population fits, e.g. between the 5 and 10-Gyr components in the upper right-hand panel of the Figure. To quantify the degree of correlation, we calculated the Spearman correlation coefficients r_s between all pairs of population components for our 12 fields. The r_s values are listed as a matrix in Table 4a, while Table 4b lists the probability that correlations as strong as indicated by

each r_s value could have occurred by chance. Ignoring the trivial diagonal elements of the matrix, we see that there are a few components that have strong anticorrelations with <10% probability of being chance correlations: the 5- and 10-Gyr components, the 10-Gyr and Z=0.03 components, the 1-Gyr and Z=0.008 component, the Z=0.0004 and Z=0.019 components, and the Z=0.019 and Z=0.03 components. These component pairs are thus probably at least partially degenerate; however, these anticorrelations do not explain away the dominance of 6+ Gyr, solar-metallicity populations in the bulge and inner disk. We also find a significant positive correlation between the 1-3 Gyr and Z=0.0001 components. This correlation suggests that the young and intermediate-age (1-3 Gyr), very metal-poor ([M/H]~ -2) populations that appear in some of the fits are due to an incomplete description of the data by our model set.

5.3. Comparison with Other Work

As demonstrated by DePoy et al. (1993), Renzini (1998), and S03, seeing-limited ground-based observations of the bulge and inner disk of M31 (e.g. Rich et al. 1993) do not have sufficient resolution to decipher the full stellar population mix. The recent work by Sarajedini & Jablonka (2005), who derived M31's bulge metallicity distribution from V and I observations taken with HST/WFPC2, thus provides the most direct comparison with our results. From the $V - I, V$ CMD of a field near F170, Sarajedini & Jablonka found a metallicity distribution peaked at [M/H]=0.0, with a gradual tail to [M/H]=−1.0 and a more rapid decline at higher metallicities. In Fig. 18, we show the metallicity distribution function and population box we derived for F170. Although our metallicity resolution is coarser than theirs, the distribution functions are in qualitative agreement. We do not find that all of the populations have ages as old as 10 Gyr, as assumed by Sarajedini & Jablonka, although these old populations do comprise the biggest component.

In Fig. 19, we show the population box integrated over all fields from our work; it is dominated by the high surface brightness bulge. Ignoring the possibly spurious intermediate-age metal-poor component, we measure a metallicity distribution function that is a bit more sharply peaked than Sarajedini & Jablonka, but is also in basic qualitative agreement. It is worthwhile to note that the 3-5 Gyr, [M/H]~ -2 component is strongest in the Bulge 1, F1, and F177 fields, and weak or non-existent in the other fields. Examining Figure 1, these fields are the three nearest the center of M31 and all lie near each other on the sky. It is perhaps tempting to speculate that the metal-poor component, if real, represents the remains of a dwarf galaxy that has merged with M31. However, in the absence of dust, such a component would make the integrated color of M31 $\sim$0.2 magnitudes bluer in $B - V$

than a purely 10 Gyr-old, solar-metallicity population, which seems ruled out by integrated surface photometry (Sandage et al. 1969). More likely is that the component appears when the crowding is most severe and the photometry is shallower.

We can also make indirect comparisons with other work. Davidge (1997) performed integrated spectroscopy of the inner few arcminutes of M31's bulge, and found Balmer indices consistent with old ($\sim$10 Gyr) stellar populations and Fe and Mg line strengths indicative of metallicities in excess of solar, in agreement with the conclusions of Spinrad & Taylor (1971). From our fits, we find a luminosity-weighted age of $>$8 Gyr for our fields with $B/D > 3$. If we consider the full fits, then the luminosity-weighted metallicity is [M/H]=-0.7; if we exclude the most metal-poor component, it is [M/H]=0.0, in good agreement with the integrated spectroscopy. Venn et al. (2000) measured elemental abundances in four young, massive supergiants from high-dispersion spectra, finding [M/H]$\sim$0.0. Jacoby & Ciardullo (1999) and Richer et al. (1999) derive median [O/H]~ -0.6 in M31 bulge PNe with a dispersion of $\sim$0.25 dex, which would be in agreement with the sense of our result if we included the most metal-poor bulge components. However, Jacoby & Ciardullo point to several factors that could bias the planetary nebula samples toward lower metallicities. Williams (2002) measured the star formation histories from WFPC2 archival images of 27 fields at radii greater than $20'$ from the center of M31. In his innermost fields, Williams found star formation histories dominated by old populations and metallicities typically in the range $-0.5 \lesssim$[Fe/H]$\lesssim 0.0$, in agreement with our inner disk and bulge star formation histories. Thus, on the whole, our derivation of M31's bulge and disk stellar populations–made solely on the basis of ground-based AO and HST/NICMOS K observations–are in excellent agreement with work done at optical wavelengths.

If we compare the star formation histories and age-metallicity relations that we derive for M31 (Figure 20) with the predictions of the simulation by e.g. Robertson et al. (2004), we conclude that the simulations appear to be on the right track to predicting the properties of galactic disks; however, we need higher quality data and improved understanding of the late stages of stellar evolution in order to provide stronger constraints from observations of nearby galaxies. We do not yet have the precision necessary to rule out the results of other simulations, such as Abadi et al. (2003).

Comparing our results for the M31 bulge with that of the Galactic bulge, we find similar stellar populations in both. Deep imaging studies of the Galactic bulge indicate that the bulk of the bulge is relatively old (Zoccali et al. 2003; Feltzing & Gilmore 2000), with an age that appears to be comparable with that of metal-rich globular clusters. The full Galactic bulge star formation history includes a fraction of stars formed at intermediate ages (Blum et al. 2003, van Loon et al. 2003), as we see in M31, but 75% have ages older than 5 Gyr.

Our results confirm those of Sarajedini & Jablonka (2005), who found remarkably similar M31 and Galactic bulge metallicity distributions, as long as we ignore the possibly spurious intermediate-age metal-poor component that appears in our solution. Comparing the M31 and Milky Way disks, by contrast, we find significant differences. Although all of our M31 fields contain a mix of some bulge and disk stars, making a unique decomposition impossible, the lack of a radial age gradient suggests that the evolution of the star formation rate with time in the disk has been similar to that of the bulge. In the Milky Way, the disk star formation history appears to have been much more constant (e.g. Hernandez et al. 2001).

6. CONCLUSIONS

We have discussed $H - K, K$ CMDs of the bulge and disk of M31 obtained with the Altair AO system and NIRI instrument on Gemini North; these are the deepest CMDs obtained to date of the inner regions of M31, and demonstrate the promise of ground-based AO for stellar populations work in the crowded regions of nearby galaxies. We have combined our K LFs with the *HST/NICMOS K* LFs published by S03 and have derived the coarse star formation history of M31's bulge and disk. By constraining the extinction to values consistent with emission by dust in the IRAS and ISO bands, we were for many of our fields able to produce statistically acceptable fits using a parameter set that included isochrones with Z={0.0001, 0.0004, 0.001, 0.008, 0.019, 0.03} and age={1, 3, 5, 10} Gyr. These fits revealed a bulge dominated by old ($\gtrsim$6 Gyr) solar-metallicity stars, in agreement with past work on the M31 bulge (Spinrad & Taylor 1971, Davidge 1997, Venn et al. 2000, Davidge et al. 2005, Sarajedini & Jablonka 2005). We find evidence for $\sim$0.5 dex lower metallicities in the disk, which is in accord with recent work indicating [Fe/H]=-0.7 in the outer disk and inner halo (Ferguson & Johnson 2001, Sarajedini & Van Duyne 2001, Durrell et al. 2004, Rich et al. 2004). Finally, we found that old populations, which we again define as having age >6 Gyr, dominate the star formation histories at all radii. Thus, we suggest that a lower bound on the redshift of formation of the disk is $z = 0.7$. Our analysis detects no age difference between the bulge and disk to the limit of our precision, leaving open the possibility that the disk formed the bulk of its stars at still higher z. The same conclusions are reached if we choose to consider the NIRI/Altair and NICMOS results separately.

Although we consider that the overall agreement of our results with that of past work represents a real success for ground-based AO-corrected imaging and photometry, there is plenty of room for improvement. On the observational side, the effects of anisoplanaticity are strong in our NIRI/Altair images; a wider field of view and more slowly varying PSF would provide definite improvement in the photometry. The recent addition of a field lens

that conjugates Altair to a layer of turbulence nearer the ground provides both of these. Additional observations would allow us to identify variable stars, which could affect the LFs of the luminous AGB population. On the analysis side, we chose a fairly crude set of basis functions to model the K LFs, yet the effects of degeneracy between our model components still remain. A better analysis would quantify more explicitly the true age and metallicity resolution of near-infrared photometry of luminous evolved stars. Finally, there remains plenty of progress to be made on stellar models of the RGB and AGB; the work by Marigo et al. (2003) and Cioni et al. (2005) are a sign of good things to come.

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Table 1.   Photometric Zero Points

| | Star with 1 ADU/s | | Guide star - Standard zero point | |
Field	H	K	$\Delta H - K$	ΔK
Bulge 1	23.92(0.02)	23.27(0.03)	0.04(0.11)	-0.04(0.06)
Bulge 2	23.92(0.02)	23.27(0.03)	-0.07(0.11)	0.14(0.06)
Disk 2	23.92(0.02)	23.27(0.03)	-0.03(0.11)	-0.27(0.06)

Table 2.   50% Completeness Limits

Field	K
Bulge 1	19.5
Bulge 2	20.5
Disk 2	20.5
F1	19.0
F2	21.0
F3	20.5
F4	21.0
F5	20.0
F170	20.5
F174	19.5
F177	19.5
F280	21.0

Table 3.   Summary of Luminosity Function Fits

ID	A_K	Age	SFR ($M_\odot$/yr^{-1}) $Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
Disk2-1	0.1	1	0.00	0.00	0.00	0.00	0.00	0.00	30.65	0.59	25.69
			(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)			
		3	0.49	0.00	0.00	1.64	0.00	0.00			
			(0.31)	(0.01)	(0.00)	(0.62)	(0.00)	(0.00)			
		5	0.00	0.00	0.00	0.00	0.00	0.95			
			(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(1.16)			
		10	0.00	0.90	2.32	0.00	0.00	3.58			
			(0.00)	(1.19)	(1.29)	(0.10)	(0.25)	(1.47)			
Disk2-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.00	28.13	0.33	34.16
		3	0.13	0.38	0.00	0.00	0.00	0.00			
		5	0.00	0.00	0.00	2.27	0.00	0.00			
		10	0.00	0.00	1.48	0.01	0.00	5.62			
Disk2-3	0.2	1	0.00	0.00	0.00	0.00	0.00	0.00	33.19	1.07	14.41
		3	0.41	0.00	0.00	2.00	0.00	0.00			
		5	0.75	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	2.83	0.00	0.00	4.69			
Disk2-4	0.1	10	0.00	2.53	1.34	7.69	0.00	1.04	179.20	22.75	0.00
Disk2-5	0.1	5	0.37	0.76	0.00	2.26	0.00	4.61	114.41	12.83	0.00
Disk2-6	0.1	3	1.46	0.00	0.00	1.83	0.01	2.66	55.17	3.99	0.07
Disk2-7	0.1	1	0.00	0.00	0.00	0.00	0.00	9.74	464.79	56.58	0.00
Disk2-8	0.1	1	0.27	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	195.93	21.60	0.00
		3	1.32	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	11.42	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Disk2-9	0.1	1	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	149.95	17.11	0.00
		3	$\cdots$	1.43	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	10.63	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Disk2-10	0.1	1	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	129.52	14.41	0.00
		3	$\cdots$	$\cdots$	1.35	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	10.18	$\cdots$	$\cdots$	$\cdots$			
Disk2-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	57.91	4.32	0.04
		3	$\cdots$	$\cdots$	$\cdots$	1.61	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	8.65	$\cdots$	$\cdots$			
Disk2-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	55.21	4.10	0.07
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.80	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.58	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	6.35	$\cdots$			
Disk2-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.08	55.82	3.72	0.13
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.87			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	5.51			

Table 3—Continued

ID	A_K	Age	Z = 0.0001	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
			SFR ($M_\odot$/yr^{-1})								
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
Bulge1-1	0.1	1	0.00	0.00	0.02	0.00	0.00	1.92	56.51	4.84	0.02
			(0.58)	(0.00)	(0.65)	(0.00)	(0.00)	(0.01)			
		3	7.42	0.00	0.00	0.00	0.00	0.00			
			(1.74)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)			
		5	9.57	0.00	0.00	0.00	0.00	0.00			
			(2.78)	(0.00)	(0.00)	(0.00)	(0.01)	(0.86)			
		10	0.00	0.00	0.00	0.00	25.73	16.06			
			(0.00)	(0.00)	(0.00)	(0.01)	(10.82)	(7.73)			
Bulge1-2	0.0	1	0.00	0.00	0.65	0.00	0.00	0.00	70.57	6.85	0.00
		3	3.72	0.00	0.00	1.78	0.00	0.00			
		5	6.68	0.00	0.00	0.00	0.00	7.79			
		10	0.00	0.00	0.01	0.01	7.68	23.49			
Bulge1-3	0.2	1	0.00	0.00	0.94	0.00	0.00	0.50	43.01	3.11	0.51
		3	5.80	0.00	0.00	0.00	5.88	0.01			
		5	17.56	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	2.58	0.00	0.00	25.11			
Bulge1-4	0.1	10	0.00	3.56	11.31	26.98	21.23	5.15	1303.26	219.82	0.00
Bulge1-5	0.1	5	20.56	0.00	0.00	7.74	3.71	14.99	647.00	104.62	0.00
Bulge1-6	0.1	3	15.02	0.00	0.00	3.60	0.00	15.99	361.76	54.48	0.00
Bulge1-7	0.1	1	0.00	0.00	0.00	4.99	0.00	34.28	1630.87	230.46	0.00
Bulge1-8	0.1	1	0.97	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	260.78	34.47	0.00
		3	6.95	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	16.41	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	50.40	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Bulge1-9	0.1	1	$\cdots$	1.27	$\cdots$	$\cdots$	$\cdots$	$\cdots$	473.23	65.37	0.00
		3	$\cdots$	4.75	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	8.77	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	55.11	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Bulge1-10	0.1	1	$\cdots$	$\cdots$	1.52	$\cdots$	$\cdots$	$\cdots$	534.17	74.94	0.00
		3	$\cdots$	$\cdots$	3.24	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	6.29	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	53.80	$\cdots$	$\cdots$	$\cdots$			
Bulge1-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	3.65	$\cdots$	$\cdots$	253.01	32.85	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	56.68	$\cdots$	$\cdots$			
Bulge1-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	3.14	$\cdots$	205.98	26.74	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	4.24	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	55.57	$\cdots$			
Bulge1-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	2.76	186.72	23.79	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot/\mathrm{yr}^{-1}$)						χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	40.57			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
Bulge2-1	0.1	1	0.00	0.00	0.29	0.00	0.00	0.00	51.44	2.87	0.72
			(0.12)	(0.00)	(0.14)	(0.00)	(0.00)	(0.00)			
		3	0.00	0.00	0.00	0.00	0.00	0.00			
			(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)			
		5	0.00	0.00	0.00	0.00	2.54	3.36			
			(0.00)	(0.15)	(0.05)	(0.11)	(1.58)	(2.55)			
		10	0.00	0.00	2.82	0.00	7.91	0.00			
			(0.00)	(0.00)	(1.33)	(0.05)	(3.69)	(0.02)			
Bulge2-2	0.0	1	0.00	0.00	0.18	0.00	0.00	0.00	55.36	3.36	0.26
		3	0.00	0.00	0.00	0.36	0.00	0.00			
		5	0.00	0.00	0.00	0.00	0.00	1.17			
		10	0.00	0.00	2.68	6.16	3.77	3.45			
Bulge2-3	0.2	1	0.00	0.00	0.33	0.00	0.00	0.00	47.31	2.44	1.59
		3	0.00	0.00	0.41	0.00	0.00	0.00			
		5	0.69	0.52	0.00	1.42	0.29	0.00			
		10	0.00	0.00	0.24	0.00	14.84	1.01			
Bulge2-4	0.1	10	0.00	0.00	2.61	9.48	7.84	0.10	238.46	31.60	0.00
Bulge2-5	0.1	5	0.15	1.24	0.01	0.00	4.77	6.68	161.62	19.70	0.00
Bulge2-6	0.1	3	1.38	0.27	0.00	1.51	0.00	6.36	172.27	20.32	0.00
Bulge2-7	0.1	1	0.00	0.00	0.00	0.00	0.00	15.70	749.36	94.04	0.00
Bulge2-8	0.1	1	0.76	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	374.34	44.16	0.00
		3	0.09	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	2.20	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	17.96	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Bulge2-9	0.1	1	$\cdots$	0.51	$\cdots$	$\cdots$	$\cdots$	$\cdots$	349.40	40.81	0.00
		3	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	2.69	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	16.44	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
Bulge2-10	0.1	1	$\cdots$	$\cdots$	0.49	$\cdots$	$\cdots$	$\cdots$	278.02	32.19	0.00
		3	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	1.34	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	17.91	$\cdots$	$\cdots$	$\cdots$			
Bulge2-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.42	$\cdots$	$\cdots$	81.43	6.57	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.39	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	18.21	$\cdots$	$\cdots$			
Bulge2-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.35	$\cdots$	61.35	4.16	0.04
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	4.02	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	13.48	$\cdots$			
Bulge2-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.42	65.88	4.80	0.02

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot$/yr^{-1})						χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	12.81			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F1-1	0.1	1	0.00	0.00	0.00	0.00	0.00	1.39	43.07	3.25	0.38
			(0.02)	(0.02)	(0.43)	(0.00)	(0.00)	(1.01)			
		3	3.97	0.00	0.00	0.00	5.95	0.00			
			(3.18)	(0.00)	(0.00)	(0.00)	(0.68)	(0.01)			
		5	33.07	0.00	0.00	0.00	0.00	0.00			
			(6.28)	(0.00)	(0.00)	(0.00)	(0.01)	(0.13)			
		10	0.00	0.00	0.00	0.00	0.00	50.64			
			(0.00)	(0.00)	(0.00)	(0.00)	(0.19)	(17.38)			
F1-2	0.0	1	0.00	0.00	0.52	0.00	0.00	0.01	45.60	3.56	0.20
		3	6.31	0.00	0.00	0.49	1.43	0.00			
		5	15.90	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	0.00	0.00	0.00	68.85			
F1-3	0.2	1	0.00	0.00	0.40	0.16	0.00	1.08	35.47	2.18	2.72
		3	3.64	0.00	0.00	0.00	9.26	0.00			
		5	44.29	0.00	0.00	0.00	0.00	0.00			
		10	0.04	0.00	0.00	0.00	0.01	37.61			
F1-4	0.1	10	0.00	40.73	0.00	80.67	0.00	0.00	839.87	147.24	0.00
F1-5	0.1	5	35.31	0.00	0.00	12.50	1.84	28.46	232.44	37.03	0.00
F1-6	0.1	3	19.63	0.00	0.00	0.35	0.00	35.60	228.78	35.17	0.00
F1-7	0.1	1	0.00	0.00	0.00	4.65	0.00	53.33	2409.54	354.41	0.00
F1-8	0.1	1	0.84	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	117.13	14.46	0.00
		3	9.33	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	25.11	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	108.53	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F1-9	0.1	1	$\cdots$	0.62	$\cdots$	$\cdots$	$\cdots$	$\cdots$	290.89	40.82	0.00
		3	$\cdots$	8.40	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	13.96	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	113.34	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F1-10	0.1	1	$\cdots$	$\cdots$	0.88	$\cdots$	$\cdots$	$\cdots$	491.23	71.96	0.00
		3	$\cdots$	$\cdots$	10.23	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	112.82	$\cdots$	$\cdots$	$\cdots$			
F1-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	3.22	$\cdots$	$\cdots$	312.93	43.15	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	99.02	$\cdots$	$\cdots$			
F1-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	3.70	$\cdots$	250.12	34.56	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	3.60	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	97.60	$\cdots$			

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Table 3—Continued

ID	A_K	Age	Z = 0.0001	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
					SFR ($M_\odot$/yr^{-1})						
F1-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	2.28	188.23	25.21	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	67.31			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F2-1	0.1	1	0.00	0.00	0.00	0.00	0.00	0.00	44.24	1.85	4.37
			(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)			
		3	0.00	0.00	0.00	0.35	0.00	0.00			
			(0.08)	(0.00)	(0.00)	(0.26)	(0.01)	(0.00)			
		5	0.00	0.00	0.00	0.30	0.00	0.00			
			(0.00)	(0.00)	(0.00)	(0.33)	(0.02)	(0.00)			
		10	0.00	0.45	0.15	0.81	0.25	0.00			
			(0.00)	(0.24)	(0.00)	(0.67)	(0.02)	(0.12)			
F2-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.00	44.33	1.94	3.74
		3	0.00	0.00	0.00	0.00	0.00	0.00			
		5	0.00	0.00	0.07	0.97	0.00	0.00			
		10	0.00	0.00	0.38	0.30	0.30	0.00			
F2-3	0.2	1	0.00	0.00	0.00	0.00	0.00	0.00	45.24	2.08	3.02
		3	0.00	0.00	0.00	0.51	0.00	0.05			
		5	0.00	0.00	0.00	0.00	0.40	0.09			
		10	0.00	0.00	0.55	0.10	0.21	0.25			
F2-4	0.1	10	0.00	0.25	0.24	2.34	0.00	0.00	96.97	9.72	0.00
F2-5	0.1	5	0.10	0.00	0.00	1.17	0.43	0.06	73.94	6.06	1.0E-03
F2-6	0.1	3	0.17	0.00	0.00	0.50	0.67	0.00	49.41	2.49	1.38
F2-7	0.1	1	0.00	0.00	0.00	0.00	0.60	1.51	194.91	19.16	0.00
F2-8	0.1	1	0.11	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	113.20	10.21	0.00
		3	0.26	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	2.46	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F2-9	0.1	1	$\cdots$	0.12	$\cdots$	$\cdots$	$\cdots$	$\cdots$	87.50	7.14	0.00
		3	$\cdots$	0.04	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	2.81	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F2-10	0.1	1	$\cdots$	$\cdots$	0.03	$\cdots$	$\cdots$	$\cdots$	72.94	5.45	4.0E-03
		3	$\cdots$	$\cdots$	0.23	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	2.41	$\cdots$	$\cdots$	$\cdots$			
F2-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	45.26	2.02	3.36
		3	$\cdots$	$\cdots$	$\cdots$	0.42	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.02	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	1.88	$\cdots$	$\cdots$			
F2-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	48.93	2.61	1.18
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.62	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.18	$\cdots$			

Table 3—Continued

ID	A_K	Age	$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
					SFR ($M_\odot$/yr^{-1})						
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.33	$\cdots$			
F2-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	55.74	3.65	0.16
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.81			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.76			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F3-1	0.1	1	0.49	0.00	0.00	0.00	0.00	0.00	40.07	1.25	10.99
			(0.13)	(0.31)	(0.01)	(0.00)	(0.00)	(0.00)			
		3	0.27	0.00	0.00	0.00	0.00	0.00			
			(0.06)	(0.00)	(0.00)	(0.03)	(0.08)	(0.00)			
		5	0.00	0.00	0.00	0.01	3.14	0.01			
			(0.10)	(0.00)	(0.01)	(0.08)	(0.08)	(0.01)			
		10	0.00	0.00	0.00	12.47	26.64	0.00			
			(0.00)	(0.00)	(0.00)	(7.46)	(7.94)	(0.05)			
F3-2	0.0	1	0.25	0.00	0.07	0.00	0.00	0.00	49.17	2.38	1.77
		3	0.00	0.00	0.00	0.66	0.00	0.00			
		5	0.00	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	0.00	16.52	23.79	0.00			
F3-3	0.2	1	0.01	0.35	0.03	0.29	0.00	0.00	32.90	0.37	32.88
		3	1.88	0.00	0.00	0.00	0.01	0.00			
		5	0.00	0.00	0.00	0.00	2.67	0.01			
		10	0.00	0.00	0.00	0.00	41.12	0.01			
F3-4	0.1	10	0.00	0.00	0.00	28.90	15.93	0.00	302.54	40.64	0.00
F3-5	0.1	5	1.11	0.00	0.00	0.00	15.26	12.04	249.30	31.63	0.00
F3-6	0.1	3	1.00	0.00	0.00	0.00	0.00	20.42	189.55	22.56	0.00
F3-7	0.1	1	0.00	0.00	0.00	0.00	0.00	29.28	1298.42	163.66	0.00
F3-8	0.1	1	0.95	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	648.18	79.56	0.00
		3	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	8.16	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	39.14	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F3-9	0.1	1	$\cdots$	1.15	$\cdots$	$\cdots$	$\cdots$	$\cdots$	627.62	76.81	0.00
		3	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	3.43	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	42.69	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F3-10	0.1	1	$\cdots$	$\cdots$	0.83	$\cdots$	$\cdots$	$\cdots$	517.90	62.98	0.00
		3	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	3.11	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	41.56	$\cdots$	$\cdots$	$\cdots$			
F3-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.65	$\cdots$	$\cdots$	57.60	3.38	0.23
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	43.19	$\cdots$	$\cdots$			
F3-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.75	$\cdots$	42.12	1.51	7.57
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot/\mathrm{yr}^{-1}$)						χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	5.61	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	35.67	$\cdots$			
F3-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.69	67.82	4.90	0.01
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.52			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	26.62			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F4-1	0.1	1	0.00	0.02	0.03	0.00	0.00	0.00	96.54	8.05	0.00
			(0.00)	(0.03)	(0.03)	(0.00)	(0.00)	(0.00)			
		3	0.00	0.02	0.00	0.00	0.00	0.00			
			(0.00)	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)			
		5	0.00	0.00	0.00	0.03	0.01	7.61			
			(0.00)	(0.11)	(0.01)	(0.01)	(0.01)	(2.24)			
		10	0.00	0.62	0.66	0.00	0.00	10.05			
			(0.01)	(0.04)	(0.82)	(0.00)	(0.04)	(3.40)			
F4-2	0.0	1	0.00	0.00	0.03	0.00	0.00	0.00	94.02	7.69	0.00
		3	0.00	0.00	0.00	0.00	0.00	0.00			
		5	0.00	0.00	0.00	0.00	0.00	5.45			
		10	0.21	0.00	0.01	0.89	0.19	11.99			
F4-3	0.2	1	0.00	0.09	0.00	0.00	0.00	0.00	117.65	10.73	0.00
		3	0.00	0.31	0.01	0.00	0.00	0.00			
		5	0.00	0.00	0.00	0.00	0.00	8.92			
		10	0.00	0.00	5.00	0.00	0.02	5.26			
F4-4	0.1	10	0.00	1.60	0.13	7.52	0.00	13.90	128.96	13.28	0.00
F4-5	0.1	5	0.00	0.00	0.00	0.00	0.00	14.85	113.48	10.87	0.00
F4-6	0.1	3	0.00	1.40	0.00	0.27	0.00	9.03	195.44	20.76	0.00
F4-7	0.1	1	0.00	1.12	0.00	0.00	0.00	12.67	1358.67	157.20	0.00
F4-8	0.1	1	0.41	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	394.36	42.65	0.00
		3	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	0.92	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	23.06	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F4-9	0.1	1	$\cdots$	0.23	$\cdots$	$\cdots$	$\cdots$	$\cdots$	329.38	35.74	0.00
		3	$\cdots$	0.44	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	22.81	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F4-10	0.1	1	$\cdots$	$\cdots$	0.21	$\cdots$	$\cdots$	$\cdots$	341.19	37.85	0.00
		3	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.64	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	22.14	$\cdots$	$\cdots$	$\cdots$			
F4-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.08	$\cdots$	$\cdots$	155.59	15.49	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	22.00	$\cdots$	$\cdots$			
F4-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.06	$\cdots$	119.99	11.01	0.00

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot$/yr^{-1}) $Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	2.56	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	19.02	$\cdots$			
F4-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.05	98.14	8.32	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	9.42			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	8.58			
F5-1	0.1	1	0.00	0.00	0.21	0.00	0.00	0.00	35.47	1.08	14.10
			(0.11)	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)			
		3	0.00	0.72	0.10	0.00	0.00	0.00			
			(0.00)	(0.14)	(0.00)	(0.04)	(0.01)	(0.00)			
		5	0.00	1.98	0.00	0.00	0.00	0.00			
			(0.01)	(0.89)	(0.02)	(0.00)	(0.00)	(4.48)			
		10	0.00	0.53	0.00	0.00	0.00	23.91			
			(0.00)	(0.01)	(0.09)	(0.00)	(0.00)	(6.41)			
F5-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.18	35.71	1.11	13.43
		3	0.00	0.96	0.00	0.00	0.01	0.09			
		5	0.00	0.78	0.00	0.00	0.00	0.13			
		10	0.00	0.00	0.00	0.00	1.94	21.57			
F5-3	0.2	1	0.00	0.00	0.41	0.00	0.00	0.00	50.91	3.19	0.37
		3	1.03	0.00	0.00	0.00	0.00	0.00			
		5	0.31	1.49	0.35	0.00	0.00	0.01			
		10	0.00	0.00	4.65	0.00	0.00	21.27			
F5-4	0.1	10	0.00	5.54	0.00	11.11	0.10	12.43	214.40	29.26	0.00
F5-5	0.1	5	0.13	1.09	0.00	1.06	0.00	16.00	89.55	9.86	0.00
F5-6	0.1	3	2.38	0.66	0.00	0.00	0.00	10.73	137.88	16.55	0.00
F5-7	0.1	1	0.00	0.00	0.00	0.00	0.00	21.46	989.30	127.42	0.00
F5-8	0.1	1	0.51	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	304.90	36.61	0.00
		3	0.33	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	3.12	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	28.80	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F5-9	0.1	1	$\cdots$	0.50	$\cdots$	$\cdots$	$\cdots$	$\cdots$	253.99	29.80	0.00
		3	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	1.89	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	28.03	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F5-10	0.1	1	$\cdots$	$\cdots$	0.36	$\cdots$	$\cdots$	$\cdots$	287.88	34.91	0.00
		3	$\cdots$	$\cdots$	0.97	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	27.14	$\cdots$	$\cdots$	$\cdots$			
F5-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.48	$\cdots$	$\cdots$	109.45	10.73	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	26.66	$\cdots$	$\cdots$			

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot$/yr^{-1})						χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
F5-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.47	$\cdots$	68.29	5.42	4.0E-03
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.14	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	27.94	$\cdots$			
F5-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.43	47.58	2.71	0.97
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	13.23			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	7.53			
F170-1	0.1	1	0.00	0.00	0.04	0.00	0.00	0.00	55.44	3.67	0.14
			(0.00)	(0.00)	(0.02)	(0.00)	(0.00)	(0.00)			
		3	0.00	0.00	0.00	1.73	0.00	0.00			
			(0.00)	(0.01)	(0.00)	(0.72)	(0.05)	(0.00)			
		5	0.00	0.00	0.00	0.00	0.00	4.73			
			(0.00)	(0.00)	(0.00)	(0.04)	(0.10)	(2.64)			
		10	0.00	0.00	2.73	0.00	4.18	4.72			
			(0.00)	(0.02)	(1.33)	(0.00)	(3.94)	(2.70)			
F170-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.00	44.98	2.44	1.63
		3	0.00	0.00	0.00	1.69	0.02	0.02			
		5	0.00	0.00	0.00	0.01	0.01	3.18			
		10	0.00	0.00	2.23	0.11	0.25	9.91			
F170-3	0.2	1	0.00	0.00	0.33	0.00	0.00	0.00	68.16	5.11	9.0E-03
		3	0.00	0.47	0.00	1.21	0.00	0.00			
		5	0.00	0.17	0.01	0.00	0.00	0.01			
		10	0.00	0.00	3.79	0.00	3.65	13.01			
F170-4	0.1	10	0.00	0.05	2.81	12.64	0.00	6.85	209.93	26.98	0.00
F170-5	0.1	5	0.03	0.00	0.00	3.10	0.00	11.16	112.82	12.51	0.00
F170-6	0.1	3	0.73	1.05	0.00	0.94	0.00	7.94	124.92	13.65	0.00
F170-7	0.1	1	0.00	0.00	0.00	0.00	0.00	17.49	881.57	109.72	0.00
F170-8	0.1	1	0.96	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	396.86	46.66	0.00
		3	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	0.79	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	22.74	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F170-9	0.1	1	$\cdots$	0.67	$\cdots$	$\cdots$	$\cdots$	$\cdots$	308.48	35.23	0.00
		3	$\cdots$	0.43	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	22.13	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F170-10	0.1	1	$\cdots$	$\cdots$	0.54	$\cdots$	$\cdots$	$\cdots$	282.63	32.63	0.00
		3	$\cdots$	$\cdots$	0.52	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	21.17	$\cdots$	$\cdots$	$\cdots$			
F170-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.21	$\cdots$	$\cdots$	97.27	8.79	0.00
		3	$\cdots$	$\cdots$	$\cdots$	1.11	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			

Table 3—Continued

| ID | A_K | Age | SFR ($M_\odot$/yr^{-1}) | | | | | | χ^2_λ | $\sigma_{\chi^2_\lambda}$ | $P_\lambda(\%)$ |
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
		10	$\cdots$	$\cdots$	$\cdots$	18.98	$\cdots$	$\cdots$			
F170-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.19	$\cdots$	70.19	5.42	2.0E-03
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.76	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.41	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	18.29	$\cdots$			
F170-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.37	71.02	5.45	1.0E-03
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.15			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	11.70			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.76			
F174-1	0.1	1	0.00	0.00	0.55	0.00	0.00	0.00	116.25	13.28	0.00
			(0.38)	(0.00)	(0.39)	(0.00)	(0.00)	(0.00)			
		3	2.15	0.00	0.00	0.00	0.09	0.00			
			(0.88)	(0.00)	(0.00)	(0.02)	(0.06)	(0.00)			
		5	0.00	0.00	0.00	0.01	0.00	0.00			
			(0.29)	(0.00)	(0.00)	(0.03)	(0.01)	(0.01)			
		10	0.00	0.00	6.14	0.00	41.89	0.05			
			(0.00)	(0.00)	(2.69)	(0.03)	(10.37)	(2.26)			
F174-2	0.0	1	0.00	0.00	0.34	0.00	0.00	0.00	109.53	12.27	0.00
		3	0.51	0.00	0.01	0.74	0.00	0.00			
		5	0.00	0.00	0.00	0.14	0.63	4.60			
		10	0.00	0.00	8.43	0.02	6.86	22.73			
F174-3	0.2	1	0.38	0.00	0.17	0.00	0.00	0.00	109.61	12.64	0.00
		3	0.00	0.00	0.00	0.00	3.28	0.01			
		5	9.67	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	4.46	0.02	32.78	0.11			
F174-4	0.1	10	0.00	0.00	9.71	23.14	15.77	3.44	442.18	71.45	0.00
F174-5	0.1	5	6.39	0.00	0.00	0.41	11.49	15.73	324.85	49.78	0.00
F174-6	0.1	3	5.31	0.00	0.00	1.74	0.00	18.48	267.15	38.32	0.00
F174-7	0.1	1	0.00	0.00	0.00	1.34	0.00	31.08	1458.78	203.11	0.00
F174-8	0.1	1	0.59	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	594.07	81.26	0.00
		3	1.66	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	12.47	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	51.71	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F174-9	0.1	1	$\cdots$	0.95	$\cdots$	$\cdots$	$\cdots$	$\cdots$	563.53	77.31	0.00
		3	$\cdots$	0.35	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	5.01	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	53.75	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F174-10	0.1	1	$\cdots$	$\cdots$	0.82	$\cdots$	$\cdots$	$\cdots$	460.46	62.81	0.00
		3	$\cdots$	$\cdots$	1.35	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.20	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	53.19	$\cdots$	$\cdots$	$\cdots$			
F174-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	1.12	$\cdots$	$\cdots$	195.20	24.04	0.00
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			

Table 3—Continued

| ID | A_K | Age | SFR ($M_\odot/\mathrm{yr}^{-1}$) | | | | | | χ^2_λ | $\sigma_{\chi^2_\lambda}$ | $P_\lambda(\%)$ |
			$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	47.34	$\cdots$	$\cdots$			
F174-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.94	$\cdots$	145.34	17.29	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.14	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	48.17	$\cdots$			
F174-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.88	163.28	20.04	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	32.18			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F177-1	0.1	1	0.00	0.00	0.00	0.00	0.00	0.26	55.56	4.70	0.02
			(0.00)	(0.00)	(0.21)	(0.00)	(0.00)	(0.08)			
		3	4.23	0.33	0.00	0.00	4.88	0.00			
			(2.49)	(0.06)	(0.00)	(0.00)	(2.06)	(0.00)			
		5	14.48	0.00	0.00	0.00	0.00	0.00			
			(4.22)	(0.00)	(0.00)	(0.00)	(0.00)	(2.28)			
		10	0.00	0.01	0.00	0.00	0.00	38.28			
			(0.00)	(0.00)	(0.06)	(0.00)	(0.05)	(11.25)			
F177-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.00	45.52	3.63	0.20
		3	7.15	0.00	0.00	1.11	0.00	0.00			
		5	1.98	0.00	0.00	0.00	0.00	0.00			
		10	0.00	0.00	0.00	0.00	0.00	52.18			
F177-3	0.2	1	0.00	0.00	0.00	0.00	0.00	0.67	51.97	4.11	0.05
		3	0.00	3.05	0.00	0.00	5.93	0.00			
		5	25.59	0.00	0.00	0.00	0.00	0.00			
		10	2.40	0.00	0.00	0.00	0.00	28.35			
F177-4	0.1	10	0.00	23.45	0.00	48.06	5.27	0.47	414.35	64.90	0.00
F177-5	0.1	5	18.32	0.00	0.00	6.81	3.45	21.79	137.07	18.60	0.00
F177-6	0.1	3	12.80	0.00	0.00	0.00	0.00	24.26	149.07	19.93	0.00
F177-7	0.1	1	0.00	0.00	0.00	0.57	0.00	44.56	1819.07	250.93	0.00
F177-8	0.1	1	0.28	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	159.29	19.45	0.00
		3	8.65	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	10.06	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	69.26	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F177-9	0.1	1	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	304.03	44.10	0.00
		3	$\cdots$	9.08	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	72.25	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F177-10	0.1	1	$\cdots$	$\cdots$	0.27	$\cdots$	$\cdots$	$\cdots$	446.55	61.67	0.00
		3	$\cdots$	$\cdots$	6.42	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	68.27	$\cdots$	$\cdots$	$\cdots$			
F177-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	2.02	$\cdots$	$\cdots$	267.25	33.56	0.00

Table 3—Continued

ID	A_K	Age	$Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
		3	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	66.40	$\cdots$	$\cdots$			
F177-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.26	$\cdots$	195.25	24.00	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	14.21	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	48.21	$\cdots$			
F177-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.24	138.60	16.08	0.00
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	45.44			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.00			
F280-1	0.1	1	0.00	0.00	0.00	0.00	0.00	0.13	25.22	-1.04	85.52
			(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)			
		3	0.01	0.02	0.00	0.17	0.00	0.08			
			(0.04)	(0.02)	(0.01)	(0.01)	(0.00)	(0.11)			
		5	0.00	0.00	0.00	0.00	0.00	0.12			
			(0.00)	(0.00)	(0.00)	(0.01)	(0.04)	(0.04)			
		10	1.13	0.00	0.09	0.00	0.00	0.21			
			(0.51)	(0.02)	(0.07)	(0.00)	(0.00)	(0.24)			
F280-2	0.0	1	0.00	0.00	0.00	0.00	0.00	0.00	23.29	-1.00	84.55
		3	0.13	0.00	0.00	0.17	0.00	0.53			
		5	0.00	0.00	0.00	0.00	0.00	0.00			
		10	0.38	0.00	0.00	0.00	0.00	0.01			
F280-3	0.2	1	0.00	0.00	0.00	0.00	0.00	0.29	23.04	-1.30	91.83
		3	0.00	0.02	0.00	0.00	0.00	0.00			
		5	0.00	0.00	0.00	0.00	0.00	0.00			
		10	1.41	0.00	0.44	0.00	0.00	0.38			
F280-4	0.1	10	1.27	0.00	0.10	0.86	0.00	0.10	143.50	16.52	0.00
F280-5	0.1	5	0.33	0.00	0.00	0.27	0.44	0.41	87.18	7.88	0.00
F280-6	0.1	3	0.22	0.08	0.00	0.28	0.00	0.49	32.75	0.31	35.35
F280-7	0.1	1	0.00	0.00	0.00	0.00	0.00	1.86	105.92	8.61	0.00
F280-8	0.1	1	0.13	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	35.98	0.25	37.22
		3	0.01	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	2.31	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F280-9	0.1	1	$\cdots$	0.06	$\cdots$	$\cdots$	$\cdots$	$\cdots$	45.78	1.66	6.01
		3	$\cdots$	0.20	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	1.87	$\cdots$	$\cdots$	$\cdots$	$\cdots$			
F280-10	0.1	1	$\cdots$	$\cdots$	0.07	$\cdots$	$\cdots$	$\cdots$	44.00	1.44	8.44
		3	$\cdots$	$\cdots$	0.18	$\cdots$	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	1.84	$\cdots$	$\cdots$	$\cdots$			

The header spanning columns $Z = 0.0001$ through 0.03 is labeled SFR ($M_\odot/\mathrm{yr}^{-1}$).

Table 3—Continued

ID	A_K	Age	SFR ($M_\odot/\mathrm{yr}^{-1}$) $Z = 0.0001$	0.0004	0.001	0.008	0.019	0.03	χ^2_λ	$\sigma_{\chi^2_\lambda}$	$P_\lambda(\%)$
F280-11	0.1	1	$\cdots$	$\cdots$	$\cdots$	0.05	$\cdots$	$\cdots$	39.44	0.85	18.94
		3	$\cdots$	$\cdots$	$\cdots$	0.39	$\cdots$	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	0.00	$\cdots$	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	1.30	$\cdots$	$\cdots$			
F280-12	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.08	$\cdots$	34.87	0.27	36.21
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.16	$\cdots$			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	1.07	$\cdots$			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.10	$\cdots$			
F280-13	0.1	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.16	30.77	-0.33	60.09
		3	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.35			
		5	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.82			
		10	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	0.11			

Table 3.   Spearman r_s Matrix

	Component									
	Age (Gyr)				Z					
Component	10	5	3	1	0.0004	0.0004	0.001	0.008	0.02	0.03
10	1.00	-0.92	-0.02	0.06	-0.08	0.11	0.13	0.47	0.28	-0.57
5		1.00	-0.26	-0.12	-0.26	-0.18	-0.04	-0.36	-0.08	0.42
3			1.00	-0.29	0.57	0.42	0.06	0.23	-0.36	-0.04
1				1.00	0.47	-0.46	-0.37	-0.58	0.35	-0.18
0.0001					1.00	-0.16	-0.38	-0.28	-0.11	0.02
0.0004						1.00	0.13	0.36	-0.71	0.20
0.001							1.00	0.26	-0.05	-0.22
0.008								1.00	-0.09	-0.39
0.02									1.00	-0.66
0.03										1.00

Table 4.   Significance Matrix

	Component									
	Age (Gyr)					Z				
Component	10	5	3	1	0.0004	0.0004	0.001	0.008	0.02	0.03
10	0.00	0.00	0.95	0.85	0.81	0.74	0.68	0.12	0.38	0.05
5		0.00	0.42	0.71	0.41	0.57	0.91	0.25	0.81	0.17
3			0.00	0.35	0.06	0.17	0.86	0.48	0.26	0.90
1				0.00	0.12	0.14	0.23	0.05	0.27	0.57
0.0001					0.00	0.62	0.22	0.38	0.74	0.95
0.0004						0.00	0.69	0.25	0.01	0.53
0.001							0.00	0.41	0.88	0.49
0.008								0.00	0.78	0.20
0.02									0.00	0.02
0.03										0.00

Fig. 1.— The locations of the NIRI/Altair fields studied in Paper I and the HST/NICMOS fields presented by S03 are shown with respect to the R-band Local Group Survey image of M31 (Massey et al. 2002).

Fig. 2.— Aperture corrections as a function of radius. The difference between the magnitudes measured within a 15-pixel radius aperture and the PSF magnitudes of the stars used to define the PSF in our Bulge 2 K image is plotted vs. radius from the central guide star. Anisoplanaticity produces a strong radial dependence of the aperture correction.

Fig. 3.— The new $H - K, K$ color-magnitude diagrams of our three NIRI/Altair fields are shown here. We attribute the small differences with the CMDs of Paper 1 to the inclusion of aperture corrections as a function of radius in the present work.

Fig. 4.— $H - K$ vs. radius from the central guide star in our Bulge 1 NIRI/Altair field. The dotted line is a fit to the points, and demonstrates that the mean $H - K$ color is independent of radius in our photometry. The dashed line is a fit to the mean color vs. radius of our Paper I photometry, which contains residual effects from uncorrected anisoplanaticity.

Fig. 5.— Simulated M31 bulge and disk stellar populations as seen by NIRI/Altair. Each simulation was produced by inserting an appropriate number of stars drawn from a 12-Gyr solar metallicity G02 isochrone into artificial images, convolving the images with our DAOPHOT/ALLSTAR PSFs, adding noise, and running the images through our photometric reduction pipeline. The photometric depths and scatter at faint magnitudes closely matches that which we observe in our fields; see text. At bright magnitudes, the scatter in color is much smaller than observed, demonstrating that the M31 fields contain a mix of stellar populations.

Fig. 6.— Photometric completeness, error, and bias in our Bulge 2 NIRI/Altair field as calculated by comparing the input and recovered photometry of 20000 artificial stars inserted into our observed images. *Top left:* Completeness versus K magnitude. *Top right:* Photometric error in K (solid circles) and $H - K$ (open circles) vs. K; overplotted are our analytical predictions using the equations from Olsen, Blum, & Rigaut (2003), with dotted line designating the K and dashed line the $H - K$ errors. The fact that the $H - K$ errors are smaller than the K errors indicates that crowding is the dominant source of error. *Bottom left:* The input minus recovered K magnitudes of our artificial stars. Below $\sim 50\%$ completeness, the photometric bias becomes large. *Bottom right:* As in bottom left, but for $H - K$. None of these quantities vary appreciably with radius from the AO guide star within the range of radii to which our photometry is restricted.

Fig. 7.— *Left:* Comparison of NIRI/Altair (red) and HST/NICMOS (black) $(H - K)_0, M_K$ color-magnitude diagrams combined over all fields. We have assumed $A_K = 0.1$ and $(m - M)_0 = 24.45$ in constructing the CMDs. *Right:* $(H - K)_0$ color distributions for all stars within 0.25 magnitudes of $M_K = -6$ for the NIRI/Altair (red) and HST/NICMOS (black) combined CMDs, normalized by the total number of stars in the distributions. The NIRI/Altair distribution lies 0.037 magnitudes to the blue of the HST/NICMOS distribution, and has scatter of 0.081 magnitudes compared to 0.064 for HST/NICMOS.

Fig. 8.— *Left:* Comparison of 2MASS PSC $(H - K)_0, M_K$ CMD of a region in the LMC Bar (red) with the Stephens et al. (2003) HST/NICMOS CMD (black) of all M31 fields combined. We have assumed $A_K = 0.1$ and $(m - M)_0 = 24.45$ in constructing the M31 CMD, and $A_K = 0.025$ and $(m - M)_0 = 18.5$ for the LMC CMD. *Right:* $(H - K)_0$ color distributions for all stars within 0.25 magnitudes of $M_K = -6$ for the 2MASS LMC Bar (red) and HST/NICMOS M31 (black) combined CMDs, normalized by the total number of stars in the distributions. The LMC Bar distribution lies 0.1 magnitudes to the blue of the HST/NICMOS distribution, as expected from the LMC's lower metallicity and younger age distribution.

Fig. 9.— As in Figure 8, but for $(J - K)_0$ instead of $(H - K)_0$. The LMC Bar color distribution appears ~ 0.05 magnitudes *redder* than the M31 color distribution, contrary to the sense of the $(H - K)_0$ distributions and to our expectations of lower metallicity and younger ages in the LMC, which should have caused the LMC Bar CMD to be ~ 0.2 magnitudes bluer than the M31 CMD in $(J - K)_0$ at $M_K = -6$. We thus propose that there is an unexplained ~ -0.25 magnitude zero point shift in the J photometry of Stephens et al. (2003).

Fig. 10.— An illustration of the sensitivity of the M_K luminosity function to age and metallicity, using the G02 isochrones. All models have been shifted vertically to match at $M_K = -4$. *Left:* The logarithmic M_K LF is shown for Z= 0.0001 (cyan), 0.0004 (blue), 0.001 (green), 0.008 (yellow), and 0.019 (red) at a fixed age of 5 Gyr. *Right:* M_K LFs are shown for ages of 1 Gyr (blue), 3 Gyr (green), 5 Gyr (yellow), and 10 Gyr (red) at fixed solar metallicity.

Fig. 11.— Test #1, demonstrating our ability to recover a simulated population mix. The input population box is shown on top left, while our derived solution is shown on top right. In the bottom panels, we show the input (dashed line) and recovered (solid line) age and metallicity distributions.

Fig. 12.— Test #2, demonstrating our ability to discriminate between 5 and 10-Gyr populations. The panels are as in Figure 11.

Fig. 13.— Test #3, testing our ability to recover the correct solution in which the input basis set does not match that used in our solution. The panels are as in Figure 11. As seen in bottom left, while we recover the correct age distribution for ages ≤5 Gyr, all of the star formation occurring at ages ≥6 Gyr gets drawn into the 10 Gyr bin.

Fig. 14.— Population boxes derived for our three NIRI/Altair fields and one of the NICMOS fields by fitting our models to the M_K luminosity functions of the data. In the columns in the middle and on the right, we show the observed (black lines with error bars) and model (red lines) luminosity functions and the residual Hess diagrams; white pixels represent areas where the data are high, while dark pixels are areas where the models predict too many stars.

Fig. 15.— The stellar populations of M31 as a function of radius. Solid circles show the results of our fits to the NIRI/Altair and NICMOS K LFs; large open circles identify the three NIRI/Altair fields. Bulge-to-disk ratios from Kent (1989) are labelled on the upper axes. *Top left:* Mean age of our population fits, integrated over all metallicities, as a function radius from the M31 center. Error bars show the rms of the age distributions. The oldest populations dominate at all radii. *Top right:* The relative contributions of each age component of the models are plotted here. Correlations between e.g. the 5- and 10-Gyr components hint at partial degeneracy between some of the components. *Bottom left:* Mean metallicities of our population fits, integrated over all ages, as a function radius from the M31 center. Error bars show the rms of the metallicity distributions. The bulge is predominantly solar metallicity; the decline in metallicity at radii below $4'$ is caused entirely by the appearance of an intermediate-age metal-poor component in the fits, which may be spurious (see text). The disk appears, on average, mbore metal-poor than the bulge. *Bottom right:* The relative contributions of each metallicity component of the models are plotted here. The components with [M/H]≥ -0.4 generally dominate.

Fig. 16.— As in Figure 15, but for the fits with $A_K = 0.0$ and $A_K = 0.2$. The overall effects of changing A_K are to make the mean metallicities ~ 0.25 dex lower in the $A_K = 0.2$ fits and ~ 0.25 dex higher in the $A_K = 0.0$ fits compared to the case of $A_K = 0.1$. With the exception of the outermost field (F280), the mean ages are ~ 1 Gyr younger in the case of $A_K = 0.2$ while the $A_K = 0.0$ mean ages are similar to $A_K = 0.1$. We conclude that our results are insensitive to changes in A_K at the ~ 0.1 magnitude level.

Fig. 17.— As in Figure 15, but choosing the fits with A_K producing highest statistical likelihood P_λ. The results are nearly identical to those of Figure 15.

Fig. 18.— The metallicity distribution function and population box of the F170 NICMOS field. Although our metallicity resolution is coarser than Sarajedini & Jablonka (2005), the distribution functions are in qualitative agreement. We do not find that all of the populations have ages as old as 10 Gyr, as assumed by Sarajedini & Jablonka, although these old populations do comprise the biggest component.

Fig. 19.— The integrated population box of M31. Because of its higher surface brightness, the bulge populations dominate the box. Although our models consisted of discrete ages from the set {1, 3, 5, 10} Gyr and discrete metallicities from the set Z={0.0001, 0.0004, 0.001, 0.008, 0.019, 0.03}, the widths of the cells in age correspond roughly to the age resolution found in our tests.

Fig. 20.— The star formation rate history and age-metallicity relation, as derived from our LF fits for all of our M31 fields combined, are plotted against those for the simulated disk galaxy of Robertson et al. (2004). Filled circles show our results excluding the [M/H]=-2.3 component; open circles includes this metal-poor component. Our age and metallicity resolution are not yet high enough to favor one numerical simulation over another.

Bulge 1

Age = 5 Gyr; Z = 0.0001, 0.0004, 0.001, 0.008, 0.019

Z = 0.019; Age = 1, 3, 5, 10 Gyr

Disk 2

Bulge 1

Bulge 2

F5